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Evaluation of the RZWQM-CERES-Maize hybrid model for maize production

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Abstract

The root zone water quality model (RZWQM) was developed primarily for water quality research with a generic plant growth module primarily serving as a sink for plant nitrogen and water uptake. In this study, we coupled the CERES-Maize Version 3.5 crop growth model with RZWQM to provide RZWQM users with the option for selecting a more comprehensive plant growth model. In the hybrid model, RZWQM supplied CERES with daily soil water and nitrogen contents, soil temperature, and potential evapotranspiration, in addition to daily weather data. CERES-Maize supplied RZWQM with daily water and nitrogen uptake, and other plant growth variables (e.g., root distribution and leaf area index). The RZWQM-CERES hybrid model was evaluated with two well-documented experimental datasets distributed with DSSAT (Decision Support System for Agrotechnology Transfer) Version 3.5, which had various nitrogen and irrigation treatments. Simulation results were compared to the original DSSAT-CERES-Maize model. Both models used the same plant cultivar coefficients and the same soil parameters as distributed with DSSAT Version 3.5. The hybrid model provided similar maize prediction in terms of yield, biomass and leaf area index, as the DSSAT-CERES

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model when the same soil and crop parameters were used. No overall differences were found between the two models based on the paired *t* test, suggesting successful coupling of the two models. The hybrid model offers RZWQM users access to a rigorous new plant growth model and provides CERES-Maize users with a tool to address soil and water quality issues under different cropping systems.
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Keywords: RZWQM; CERES; DSSAT; System modeling; Agricultural management; Plant growth modeling; Water stress; Nitrogen stress

1. Introduction

The root zone water quality model (RZWQM) was first released in 1992 (Ahuja et al., 2000a) and has been extensively evaluated for soil water movement (Ahuja et al., 2000b), soil heat transport (Ma et al., 1998a), pesticide transport (Malone et al., 2004), nitrogen (N) management (Ma et al., 1998b), and crop growth (Ma et al., 2003). The strengths of the RZWQM include macropore flow, tile drainage simulation, water table fluctuation, soil microbial population simulation, plant population development, and management effects (Ahuja et al., 2000a; Ma et al., 2000). It has a detailed soil water balance routine using the Green-Ampt equation for water infiltration and the Richards' equation for water redistribution (Ahuja et al., 2000b). Surface crusting and soil macropore flow are also considered (Ahuja et al., 2000b). The detailed soil carbon/nitrogen dynamics module contains two surface residue pools, three soil humus pools, and three soil microbial pools. It simulates N mineralization, nitrification, denitrification, ammonia volatilization, urea hydrolysis, methane production, and microbial population. These processes are functions of soil pH, soil O_2, soil microbial population, soil temperature, soil water content, and soil ion strength (Shaffer et al., 2000). RZWQM has an extended Shuttleworth–Wallace potential evapotranspiration (PET) module that considers the effects of surface crop residue cover on aerodynamics (Farahani and DeCoursey, 2000). The generic plant growth model simulates crop yield, biomass, leaf area index, root biomass, and rooting depth (Hanson, 2000); however, it does not simulate leaf number, phenological development, and other yield components. As a greater number of RZWQM applications focused on crop production under different management conditions, there existed a need to improve the generic plant growth model in RZWQM for simulating detailed plant growth components (Ma et al., 2000; Ahuja et al., 2002).

Another widely used model is the DSSAT (Decision Support System for Agrotechnology Transfer) family of models (Tsuji et al., 1994; Ritchie et al., 1998; Hoogenboom et al., 1999; Jones et al., 2003). It contains two crop specific plant growth models (CERES and CROPGRO). These crop models simulate detailed yield components, leaf numbers, and phenological development. In addition, they have been evaluated all over the world. Many crop modelers are continuously working on these models to improve and extend their applicability (Pedersen et al., 2004; Sau et al., 2004; Lizaso et al., 2001), although both the CROPGRO and CERES models have shown various deficiencies in simulating maize production for some applications (Sadler et al., 2000; Ma et al., 2002). Sadler et al. (2000) showed that the CERES-Maize model was insensitive to soil type, depth to clay, and soil nitrogen and recommended a more mechanistic approach to soil water and nitrogen balances. A previous study showed that a hybrid model between the RZWQM and DSSAT-CROPGRO models improved the simulation of soybean production systems under dryland conditions (Ma et al., 2005). They claimed that the RZWQM-CROPGRO hybrid model not only provided RZWQM users a valid option of a new plant growth module, but also extended CROPGRO to a wide soil conditions. Recently, DSSAT users have requested components for tile flow (Shen et al., 1998; Garrison et al., 1999), water table fluctuation (Gerakis and Ritchie, 1998), pesticide leaching (Gerakis and Ritchie, 1998), tillage (Andales et al., 2000), and better C/N dynamics (Gijsman et al., 2002) into the DSSAT simulation models.

The objective of this study was to develop and evaluate an RZWQM-CERES-Maize hybrid model for maize production. Simulated soil water and soil nitrogen (N) balances were also examined in comparison with results from the original DSSAT-CERES-Maize model. We also investigated the responses of both models to water and N stresses under different irrigation and N treatments.

2. RZWQM-CERES hybrid model

To develop a linkage between RZWQM and CERES-Maize, it was necessary to understand the components of each model and their data requirements. Since the purpose of this linkage was to integrate the growth and development components of CERES-Maize model into RZWQM as an option for crop production simulation in RZWQM, we kept the integrity of the CERES-Maize model as much as possible to preserve the cultivar and other genetic coefficients. Specifically, RZWQM provided CERES-Maize with the daily soil water and nitrogen (N) contents, daily potential evapotranspiraton (PET), and daily soil temperature, in addition to daily weather data (maximum and minimum daily air temperature, solar radiation). The CERES-Maize model supplied RZWQM with daily plant water uptake, N uptake, and plant growth variables (e.g., leaf area index, root distribution, and crop residue at harvest). We used PET estimates from RZWQM to capture crop residue and wind effects as calculated from the Shuttleworth–Wallace equations (Shuttleworth and Wallace, 1985), rather than the Priestley–Taylor equations implemented in CERES-Maize (Priestley and Taylor, 1972; Ritchie, 1998). Daily water and N stress factors were calculated by CERES-Maize based on RZWQM-provided soil water, N content, and PET (Ritchie, 1998; Godwin and Singh, 1998).

Two water stress factors in the CERES model are defined from the ratio of potential root water uptake to potential transpiration: one for photosynthesis and the other for plant growth. The water stress factor presented in this study is the water stress factor for plant growth:

$$\text{Daily water stress factor} = \frac{\sum \mathrm{RWU}(L) * \mathrm{RLV}(L) * \Delta L}{1.5 \text{ potential transpiration}}. \tag{1}$$

Potential water uptake per unit root length is calculated from soil water availability and plant root distribution (Ritchie, 1998):

$$\mathrm{RWU}(L) = \frac{k_1 * \mathrm{e}^{k_2 * (\mathrm{SW}(L) - \mathrm{LL}(L))}}{k_3 - \ln(\mathrm{RLV}(L))}, \tag{2}$$

where RWU(L) is potential root uptake per unit root length for soil layer L (cm^3 water per cm root); RLV(L) is the root length density in the soil layer (cm root per cm^3 soil); SW(L) and LL(L) are current soil water content and the lower limit of plant available water in the soil layer (cm^3 cm^{-3}), respectively; and k_1, k_2, and k_3 are constants (dimensionless). In DSSAT v3.5, $k_1 = 1.32 \times 10^{-3}$, $k_2 = 120 - 250\mathrm{LL}(L)$, and $k_3 = 7.01$. Potential transpiration is calculated from Shuttleworth–Wallace equations in RZWQM.

Plant N stress factor is calculated from a nitrogen deficiency index (NFAC) in the CERES model (Godwin and Singh, 1998):

$$\mathrm{NFAC} = 1.0 - \frac{\mathrm{TCNP} - \mathrm{TANC}}{\mathrm{TCNP} - \mathrm{TMNC}} \tag{3}$$

where TCNP, TMNC, and TANC are critical, minimum, and actual plant N concentrations. TCNP and TMNC are functions of growth stage (XSTAGE = 0–7):

$$\mathrm{TCNP} = \frac{\mathrm{e}^{1.52 - 0.16 * \mathrm{XSTAGE}}}{100} \tag{4}$$

and

$$\mathrm{TMNC} = \frac{1.25 - 0.20 * \mathrm{XSTAGE}}{100} \quad \text{when XSTAGE} < 4.0, \tag{5}$$

$$\mathrm{TMNC} = 0.0045 \quad \text{when XSTAGE} \geqslant 4.0.$$

A Fortran subroutine was created to facilitate data and information transfer between RZWQM and CERES-Maize (both are in Fortran code). Since RZWQM and CERES-Maize use different numerical grids for the soil profile, the subroutine converts soil water, soil N, and soil temperature from one grid to another on a daily basis. We also assume that the drained upper limit (DUL) and lower limit (LL) of plant available water in CERES to be the soil water contents at 33 and 1500 kPa water potentials in RZWQM, respectively (Ritchie, 1998). After the hybrid was developed, the RZWQM-CERES model was verified numerically for correct exchange of variables between the two models before it was evaluated against experimental data.

Crop cultivar parameters are managed by a Windows™ interface in RZWQM-CERES and users can select a cultivar from the DSSAT genotype database or create a new cultivar. Simulation controls and the root growth distribution factor (SRGF) are also facilitated by a Windows™ interface. These Windows™ interfaces are part of the crop management options in RZWQM-CERES model, and users can activate the CERES plant growth module by simply selecting a cultivar from the DSSAT genotype database and then modifying its parameters if necessary. Output files generated by the hybrid model have the same formats as in the original DSSAT-CERES model.

3. Materials and methods

Two datasets released with the DSSAT models (v3.5) were selected for the evaluation because of their completeness in fertilizer and irrigation treatments and can be obtained from the International Consortium for Agricultural System Applications (ICASA) Data Exchange (Bostick et al., 2004). The first is a maize study conducted at the University of Florida, Gainesville, Florida, USA, in 1982 (UFGA8201), where two nitrogen levels (62 and 275 kg N ha^{-1}) and three irrigation treatments (no-irrigation, full-irrigation and vegetative stress irrigation) were implemented (Bennett et al., 1986). The soil was a Millhopper fine sand (loamy, siliceous, hyperthemic Grossarenic Paleudults). The maize variety McCurdy 84AA[1] was planted on February 26, 1982, in 61-cm rows with 23 cm between seeds to a population of 71000 plants ha^{-1}. Water was applied by over-head sprinklers. The two irrigation treatments were similar except for a 10-day water stress period prior to 50% silking (May 2 to May 10) in the vegetative stress treatment. Nitrogen was sidedressed at 27 and 35 kg N ha^{-1} on April 7 and 12, respectively, for the low N treatment and at 56, 52, 75, 37, and 55 kg N ha^{-1} on March 15 and 30, April 12 and 28, and May 7, respectively, for the high N treatment. Available experimental measurements included grain weight, grain number, leaf area index (LAI), aboveground biomass, and dates for flowering and physiological maturity. The observed physiological maturity date was July 4, 1982.

The second maize dataset from DSSAT v3.5 was from a study conducted in Waipio, Oahu, Hawaii, USA in 1983 (IBWA8301). The soil was a Wahiawa silty clay (Clayey, kaolinitic, isohyperthermic, Tropeptic Eutrustox). The two varieties that were tested included Pioneer 304 and UH610. Maize was planted on November 30, 1983, to a density of 58,000 plants ha^{-1}. Furrow irrigation was started on December 3, 1983, and ended on March 29, 1984 with a total of 304 mm water applied. Three nitrogen treatments were no N application, 50, and 200 kg N ha^{-1}. Urea was applied on November 29, 1983, and January 6 and February 10, 1984, in equal amounts. Available field measurements included grain weight, weight per grain, grains per ear, LAI, and biomass (Singh, 1985). The observed physiological maturity dates ranged from April 11 to April 17, 1984, depending on the variety and treatment.

Model performance was compared to measured data and simulation results from the original CERES-Maize (Version 3.5) using root mean square errors (RMSE) and

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[1] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors or the USDA.

the paired *t* test. The paired *t* test tests differences between simulation errors (absolute differences between simulated and measured values) of the RZWQM-CERES-Maize and DSSAT-CERES-Maize models.

4. Results and discussion

4.1. Calibration of the RZWQM-CERES hybrid model

Since both datasets were simulated and released with DSSAT v3.5, no further adjustments were made to the DSSAT-CERES model parameters and simulation results. To evaluate the RZWQM-CERES hybrid model using these datasets, we assumed the DUL to be the soil water content at 33 kPa tension and the LL to be the soil water content at 1500 kPa tension as suggested by Ritchie (1998) (Table 1). We also used the same saturated soil water contents as in the original DSSAT-CERES model, although the saturated soil water contents were much lower than porosity for the Millhopper fine sand. The Brooks–Corey parameters were then calculated from these soil water contents and used in RZWQM-CERES hybrid model

Table 1
Soil Properties of the original CERES-Maize model (v3.5) and for testing of the RZWQM-CERES hybrid model

Soil layer (cm)	Bulk density (g cm^{-3})	Organic C %	SRGF# (dimensionless)	Initial SWC	LL	DUL	SAT
				(cm^3 cm^{-3})			
Wahiawa silty clay							
0–5	1.00	2.21	1.00	0.260	0.220	0.350	0.550
5–15	1.00	2.21	1.00	0.260	0.230	0.350	0.550
15–30	1.05	1.05	0.80	0.300	0.240	0.350	0.550
30–45	1.17	1.40	0.40	0.370	0.250	0.370	0.480
45–60	1.20	1.04	0.27	0.337	0.257	0.377	0.467
60–90	1.22	0.58	0.10	0.300	0.253	0.380	0.460
90–108	1.17	0.27	0.02	0.320	0.260	0.400	0.480
Millhopper fine sand							
0–5	1.30	2.00	1.00	0.086	0.026	0.096	0.230
5–15	1.30	1.00	1.00	0.086	0.025	0.086	0.230
15–30	1.40	1.00	0.80	0.086	0.025	0.086	0.230
30–45	1.40	0.50	0.20	0.086	0.025	0.086	0.230
45–60	1.40	0.50	0.20	0.086	0.025	0.086	0.230
60–90	1.45	0.10	0.10	0.076	0.028	0.090	0.230
90–120	1.45	0.10	0.05	0.076	0.028	0.090	0.230
120–150	1.45	0.04	0.00	0.130	0.029	0.130	0.230
150–180	1.20	0.24	0.00	0.258	0.070	0.258	0.360[a]

SRGF, soil root growth factor; LL, lower limit of plant available water; DUL, drained upper limit; SAT, saturated soil water content; SWC, soil water content; C, carbon.

[a] Saturated soil water content for the Millhopper fine sand at depth of 150–180 cm depth was 0.547 from soil bulk density because the 0.360 used in DSSAT did not calculate valid Brooks–Corey parameters.

Table 2
Cultivar parameters of the CERES-Maize model

Parameter name	Cultivar coefficients			Definition
	McCurdy84aa	Pioneer 304	UH610	
P1	385	265	345	Thermal time from seedling emergence to the end of the Juvenile phase (expressed in degree days above a base temperature of 8 °C) during which the plant is not responsive to changes in photoperiod
P2	0.52	0.30	0.52	Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 h)
P5	940	940	920	Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8 °C)
G2	687.5	770.0	638.0	Maximum possible number of kernels per plant
G3	6.0	8.0	6.4	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day)
PHINT	38.9	38.9	38.9	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances

The values are the original ones as distributed with DSSAT Version 3.5 (Hoogenboom et al., 1999).

(Ahuja et al., 2000b). Saturated soil hydraulic conductivities for each soil layer were estimated from the soil texture class as in Rawls et al. (1982).

Since the weather data of these experimental data sets did not include wind run and rainfall intensity, we used the default wind run of 100 km/day breeze in RZWQM for the calculation of potential evapotranspiration (PET) as required by the Shuttleworth–Wallace PET module (Farahani and DeCoursey, 2000), and assumed 2 h duration for all the rainfall events. Simulation runs started on February 26, 1982 for the Gainesville, Florida study and on November 22, 1983 for the Waipio, Hawaii study for both the RZWQM-CERES hybrid model and the DSSAT-CERES-Maize model. Identical cultivar coefficients were used for the RZWQM-CERES hybrid model and the DSSAT-CERES model for all three cultivars (Table 2). Also, the same soil root growth factors (SRGF) and fertilizer factors were used in the hybrid model and in the DSSAT-CERES model (Table 1).

In the DSSAT-CERES model, one humus pool was used for soil organic matter and no microbial population was simulated (Godwin and Singh, 1998). However, in the RZWQM-DSSAT hybrid model, there were three humus pools and three microbial pools (Ma et al., 1998b; Ma and Shaffer, 2001). To initialize the soil organic pools in RZWQM-CERES model, we used the default soil microbial pools for the soil surface layer (Ma et al., 1998b) and then partitioned soil organic pools to match the total amount of organic N mineralized to that simulated by DSSAT-CERES model during the crop growing season (Table 3). Specifically, for the Wahiawa silty

Table 3
Initial soil organic and soil microbial pools used in the RZWQM-CERES hybrid model

Soil depth (cm)	Fast humus pool (μg C/g soil)	Transient humus pool (μg C/g soil)	Stable humus pool (μg C/g soil)	Aerobic heterotrophs (no./g soil)	Autotrophs (no./g soil)	Anaerobic heterotrophs (no./g soil)	NO_3-N[a] Conc. (μg N/g soil)	NH_4-N Conc. (μg N/g soil)
Wahiawa silty clay[a]								
0–5	293	2641	19,639	100,000	1000	10,000	4.5	2.9
5–15	293	2641	19,639	100,000	1000	10,000	3.2	2.4
15–30	139	1257	9352	47,619	476	4761	1.5	1.7
30–45	181	1635	12,158	61,904	619	6190	0.5	1.1
45–60	111	999	7435	37,857	378	3785	0.3	0.9
60–90	56	509	3787	19,285	192	1928	0.3	0.3
90–108	34	314	2338	11,904	119	1190	0.2	0.2
Millhopper fine sand								
0–5	4670	5266	9937	100,000	1000	10,000	0.6	1.5
5–15	2335	2633	4968	50,000	500	5000	0.6	1.5
15–30	2335	2633	4968	50,000	500	5000	0.6	1.5
30–45	1173	1323	2497	25,135	251	2513	0.6	1.5
45–60	1173	1323	2497	25,135	251	2513	0.6	1.5
60–90	233	263	496	5000	50	500	0.6	0.6
90–120	233	263	496	5000	50	500	0.6	0.5
120–150	88	99	188	1891	18	189	0.6	0.5
150–180	555	626	1181	11,891	118	1189	0.6	0.5

[a] Initial soil NH_4-N and NO_3-N concentrations changed from treatment to treatment. Values listed for the Wahiawa silty clay soil were averages across treatments. Microbial population was shown as number of organisms per gram of soil.

clay, the DSSAT-CERES model simulated 49 kg N ha^{-1} of mineralized N from soil organic matter for the zero fertilizer treatment. Therefore, the RZWQM-CERES hybrid model was calibrated for the zero fertilizer treatment and the calibrated model provided 48 kg N ha^{-1} of mineralized N from soil organic matter by assuming 1.3% of soil organic C in the fast humus pools, 11.7% in the intermediate humus pool, and 87% in the slow humus pool (Table 3). For the Millhopper fine sand, the DSSAT-CERES model simulated 35 kg N ha^{-1} of mineralized N from soil organic matter during the crop growing season for the rainfed low N treatment, and we found that the RZWQM-CERES hybrid model simulated the same amount of mineralized N by assuming 23.5% of soil organic C in the fast humus pool, 26.5% in the intermediate humus pool, and 50% in the slow humus pool (Table 3). For both soils, we assumed that the partition percentages were invariable with soil depth. It is worth mentioning that the partitioning percentages of soil carbon pools will change if a different microbial population is used.

Although both models had exactly the same soil organic C input, RZWQM-CERES calculated slightly different total soil organic N than DSSAT-CERES. The reason was that the DSSAT-CERES model used a default C/N ratio of 10 for the given organic C, whereas RZWQM-CERES had three organic pools with C/N ratios of 8, 10, and 11, and total soil organic N depended on the partitioning among the pools. For the Millhopper fine sand soil, DSSAT-CERES estimated initial soil organic N of 8708 kg N ha^{-1} comparable to the 8735 kg N ha^{-1} by RZWQM-CERES. However, for the Wahiawa silty clay soil, DSSAT-CERES and RZWQM-CERES calculated initial soil organic N of 11,400 and 11,200 kg ha^{-1}, respectively. The lower initial soil organic N estimated by RZWQM-CERES was due to higher percentage of slow humus pool (87%) that has a C/N ratio of 11. Nonetheless, the difference was only 1.7% and both models simulated the same amount of N mineralization.

4.2. Soil water and nitrogen balance simulation

After calibrating the soil organic C pools to match mineralized N in both models, The RZWQM-CERES model was run for both datasets and the results were compared to those from the DSSAT-CERES model. In general, both models simulated similar PET and actual ET (AET) (Figs. 1 and 2). For the Gainesville, Florida study, on the average across all treatments, RZWQM-CERES simulated 50 mm more PET than DSSAT-CERES during the growing seasons (541 mm vs. 591 mm). Simulated average AET was 93 mm higher by RZWQM-CERES (514 mm) than by DSSAT-CERES (421 mm) during the same period of time due to higher soil water content simulated in RZWQM-CERES model. Both models simulated about 100 mm increase in AET from rainfed treatment to irrigated treatments (full and vegetative stress). AET did not vary between the 62 and 275 kg N ha^{-1} treatments, however. DSSAT-CERES simulated between 33 and 37 mm of runoff water during the growing seasons for all the treatments, whereas RZWQM-CERES simulated no runoff for the rainfed treatments and 21 mm for the irrigated treatments due to the 2 h rainfall duration assumed. DSSAT-CERES also simulated about 100 mm more water

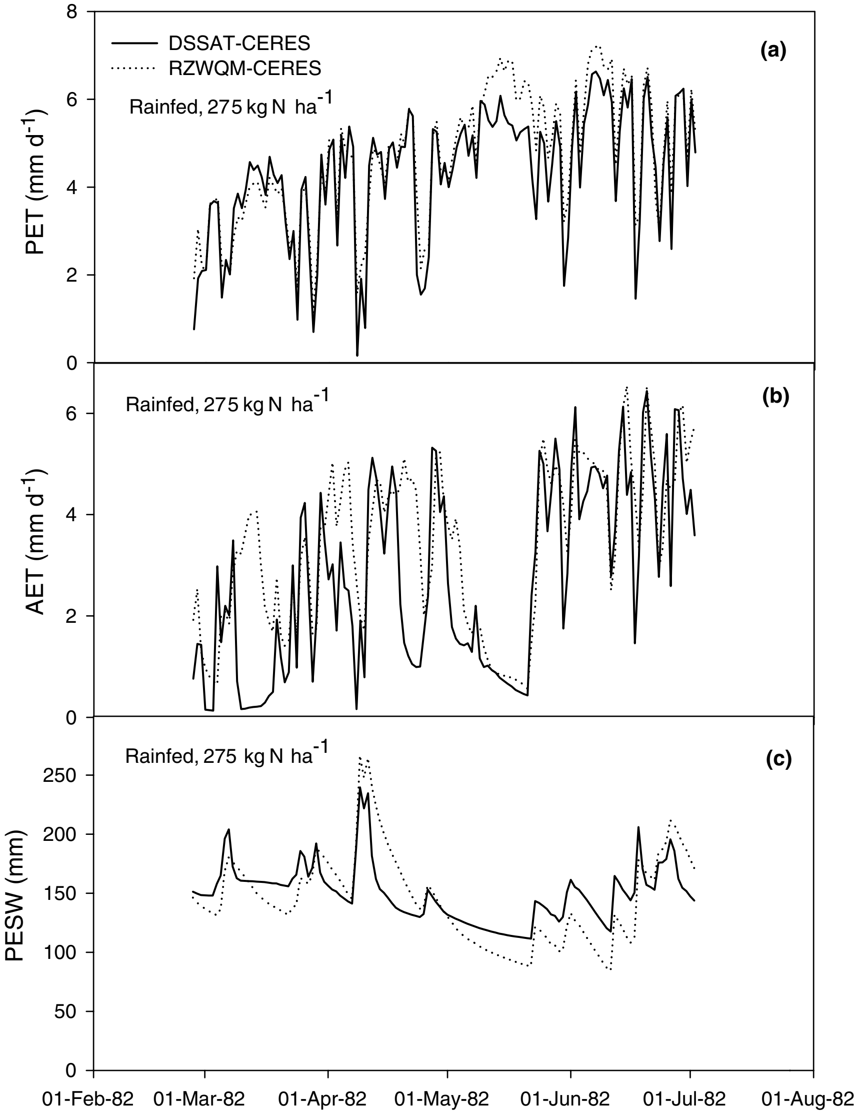

Fig. 1. Simulated potential evapotranspiration (PET) (a), actual evapotranspiration (AET) (b), and plant extractable soil water (PESW) (c) by both RZWQM-CERES and DSSAT-CERES models for rainfed condition with a 275 kg N ha^{-1} application rate in the Gainesville, Florida study.

drainage out of the soil profile than RZWQM-CERES. Both models simulated 50–120 mm more drainage under irrigated conditions than under rainfed conditions. DSSAT-CERES model simulated 5–7 mm less plant extractable soil water (PESW) at the end of the growing seasons than at the beginning of growing season, whereas the RZWQM-CERES model simulated 13–39 mm more PESW at the end of grow-

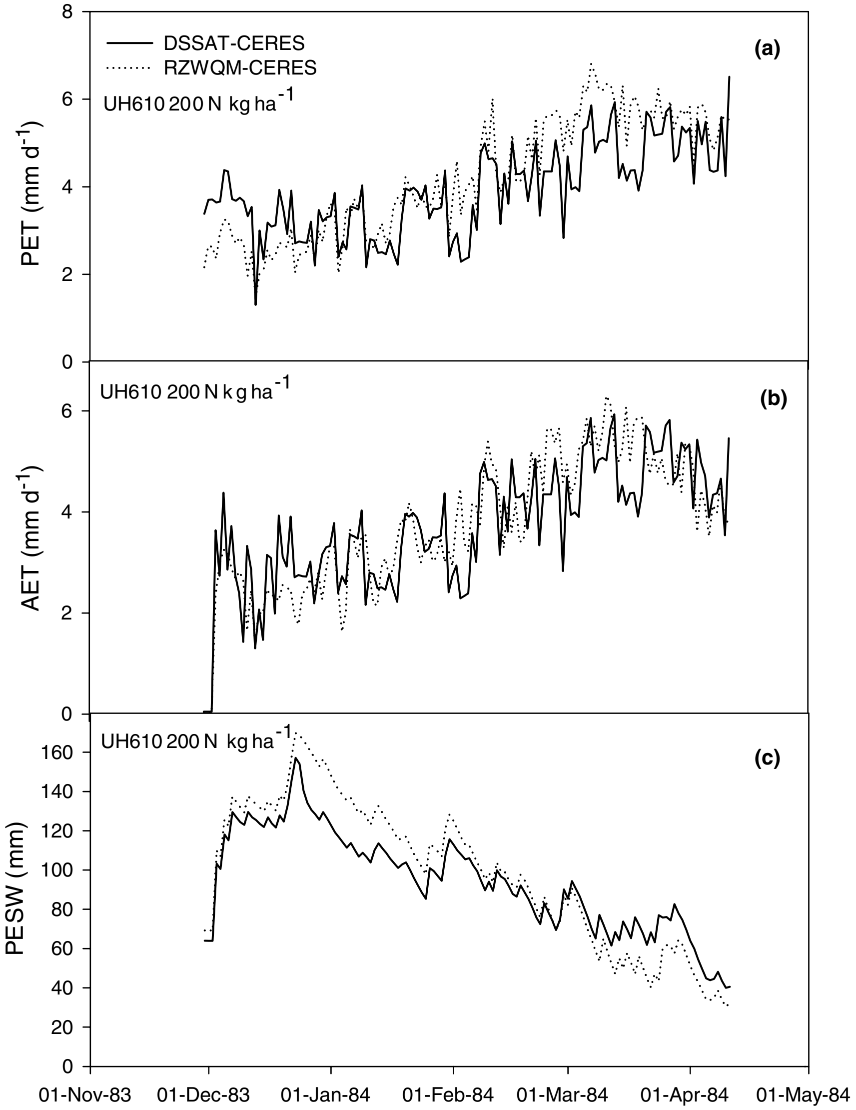

Fig. 2. Simulated potential evapotranspiration (PET) (a), actual evapotranspiration (AET) (b), and plant extractable soil water (PESW) (c) by both RZWQM-CERES and DSSAT-CERES models for the UH610 variety and 200 kg N ha^{-1} application rate in the Waipio, Hawaii study.

ing seasons than at the beginning of growing seasons (Fig. 1). Therefore, the RZWQM-CERES hybrid model simulated less drought stress than DSSAT-CERES model due to less water drainage (Fig. 3).

For the Waipio, Hawaii study, RZWQM-CERES model again simulated a PET that was 48 mm more than the PET simulated by the DSSAT-CERES model during

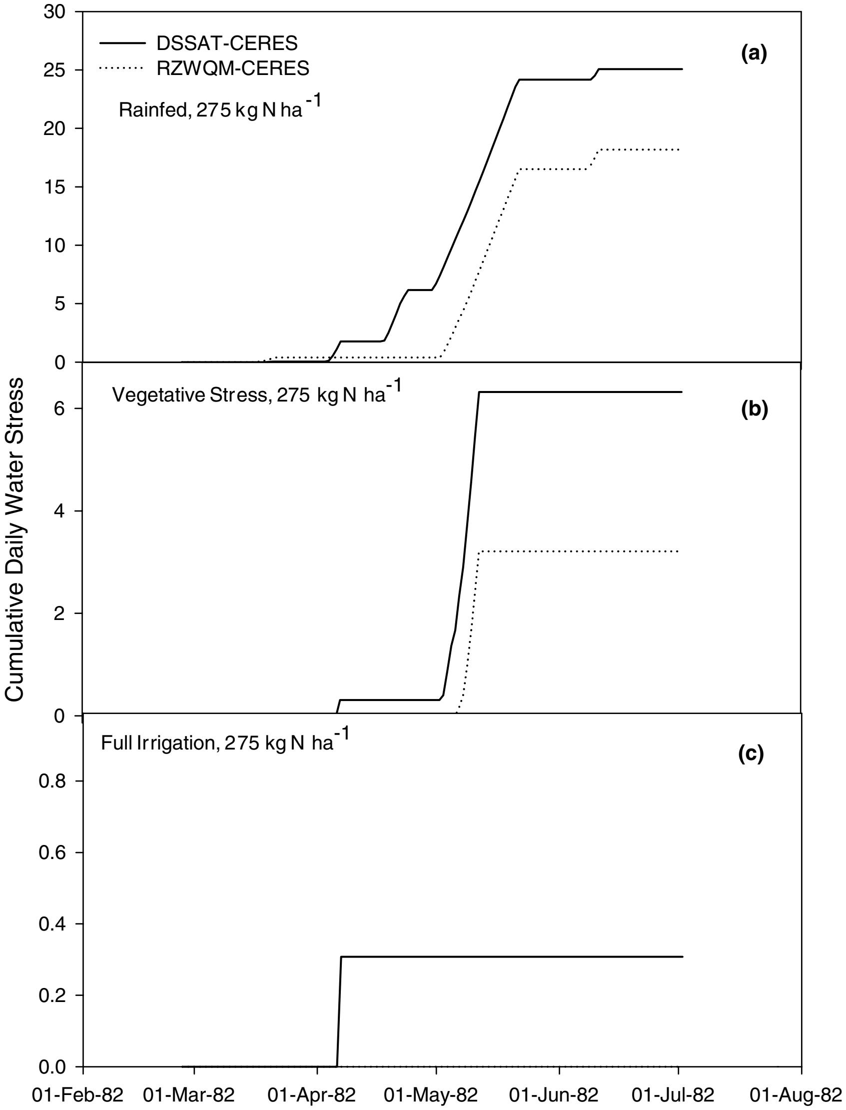

Fig. 3. Simulated cumulative daily water stress factors for plant growth by the RZWQM-CERES and the DSSAT-CERES models for the 275 kg N ha^{-1} application rate under rainfed (a), vegetative stress (b) and full irrigated (c) conditions in the Gainesville, Florida study.

the growing seasons (541 mm vs. 589 mm) (Fig. 2). Simulated AET was very similar for both models during the same period of time (519 mm in DSSAT-CERES and 516 mm in RZWQM-DSSAT). Therefore, only a minor drought stress was simulated by both models (Fig. 4). Also, no runoff water was simulated by either model. RZWQM-CERES simulated an average of 22 mm drainage as compared to

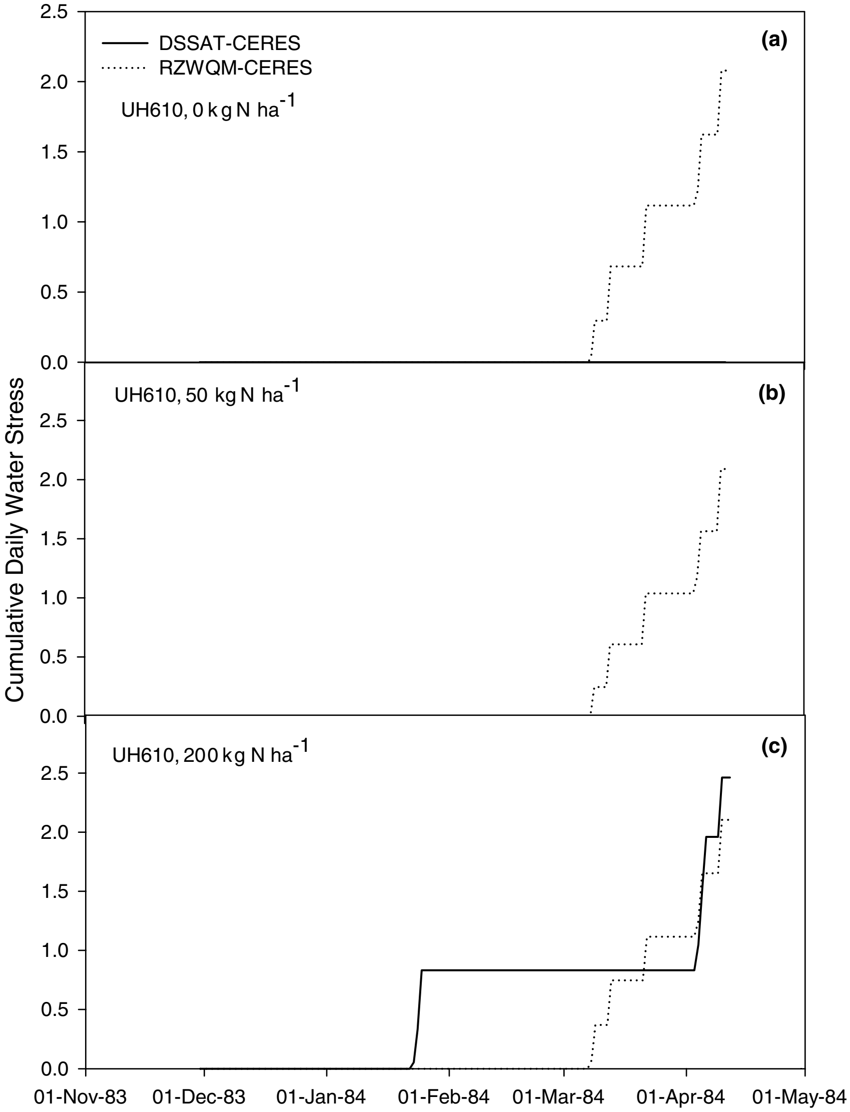

Fig. 4. Simulated cumulative daily water stress factors for plant growth by the RZWQM-CERES and the DSSAT-CERES models for the UH610 variety with 0 kg N ha^{-1} (a), 50 kg N ha^{-1} (b), and 200 kg N ha^{-1} (c) application rates of the Waipio, Hawaii study.

16 mm by the DSSAT-CERES model. Simulated PESW was comparable in both models (Fig. 2). RZWQM-CERES model mined 40 mm of PESW and DSSAT-CERES mined 33 mm of PESW during the growing seasons. DSSAT-CERES simulated a slightly decrease in PESW with increase in N application, which was responsible for the water stress simulated at 200 kg N ha^{-1} application rate (Fig. 4).

The soil N balance was evaluated based on N additions to soil via mineralization and fertilization, N leaching, and N uptake. For the Gainesville, Florida study, both models simulated slightly higher N mineralization with increasing irrigation amounts, from 35 to 43 to 47 kg N ha^{-1} for DSSAT-CERES and from 35 to 50 to 65 kg N ha^{-1} for RZWQM-CERES as treatments varying from rainfed to vegetative stress irrigation to full irrigation, of which 10–20 kg N ha^{-1} was immobilized by microbes in the RZWQM-CERES. Thus, net N mineralization was less in RZWQM-CERES than in the DSSAT-CERES model. Although the DSSAT-CERES model also simulated immobilization of N, the microbial biomass was part of the soil organic N pools. DSSAT-CERES model simulated higher N leaching than RZWQM-CERES due to the higher amount of drainage. RZWQM-CERES model simulated higher N uptake (4–16% higher for the low N treatments and 11–50% higher for the high N treatments) than DSSAT-CERES model due to high biomass simulated (Table 4). However, the RMSE of simulated N uptake was 37.0 kg N ha^{-1} for DSSAT-CERES and 36.5 kg N ha^{-1} for RZWQM-CERES and no difference was found in N uptake based on the paired *t* test. Both models also correctly simulated higher N uptake at the 275 kg N ha^{-1} application rate than at the 62 kg N ha^{-1} application rate, and a higher N uptake under irrigated than under rainfed conditions. RZWQM-CERES model simulated less soil inorganic N at the end of harvest than DSSAT-CERES. RZWQM-CERES mined an average of 17 kg N ha^{-1} of inorganic N from the soil profile compared to 11 kg N ha^{-1} by DSSAT-CERES at 62 kg N ha^{-1} treatment. Under full irrigated conditions, and at a 275 kg N ha^{-1} application rate, DSSAT-CERES mined 4 kg N ha^{-1} of inorganic N during the growing season because of extensive N leaching, whereas RZWQM-CERES model gained 0.4 kg N ha^{-1} of inorganic N into the soil profile. Under the rainfed condition and at a 275 kg N ha^{-1} application rate, DSSAT-CERES gained 111 kg N ha^{-1} of inorganic N and RZWQM-CERES gained 44 kg N ha^{-1} in the soil at harvest time. For the vegetative stress conditions and a 275 kg N ha^{-1} rate, DSSAT-CERES gained 14 kg N ha^{-1} of inorganic N and RZWQM-CERES gained 7 kg N ha^{-1} in the soil profile at harvest. Because of low simulated soil inorganic N, the RZWQM-CERES model simulated higher N stress than the DSSAT-CERES model (Fig. 5). However, both models simulated lower N stress under rainfed conditions than under irrigated conditions due to less N leaching (Fig. 5).

For the Waipio, Hawaii study, both models simulated about 50 kg N ha^{-1} mineralized during the growing seasons, of which 20 kg N ha^{-1} was immobilized to microbial biomass in RZWQM-CERES. No N leaching was simulated by either model. For both maize varieties, RZWQM-CERES simulated 30% less N uptake for the 0 kg N ha^{-1} treatment, 17% less N uptake for the 50 kg N ha^{-1} treatment, and 5–10% higher N uptake for the 200 kg N ha^{-1} treatment than DSSAT-CERES model. The RMSE for simulated N uptake was 40.8 kg N ha^{-1} for the DSSAT-CERES and 41.6 kg N ha^{-1} for the RZWQM-CERES model, with no difference found in N uptake based on the paired *t* test. At harvest, the RZWQM-CERES model simulated only 5 kg N ha^{-1} of inorganic soil N compared to 11 kg N ha^{-1} simulated by DSSAT-CERES model, which contributed to the higher N stress simulated by RZWQM-CERES (Fig. 6).

Table 4
Measured and simulated maize productions using DSSAT-CERES and RZWQM-CERES models for the Gainesville, Florida and the Waipio, Hawaii studies

Treatment		Grain yield (kg ha^{-1})			Harvested biomass (kg ha^{-1})			Maximum LAI		
Water/Variety	Nitrogen (kg ha^{-1})	Observed	DSSAT-CERES	RZWQM-CERES	Observed	DSSAT-CERES	RZWQM-CERES	Observed	DSSAT-CERES	RZWQM-CERES
Gainesville, Florida study										
Rainfed	62	2929	2155	1954	5532	6612	7733	2.26	2.06	3.24
Rainfed	275	3130	2306	2772	7201	7036	9792	2.84	2.16	3.60
Irrigation	62	6850	6247	6663	14,581	13,745	14,373	3.26	3.98	4.17
Irrigation	275	11,881	10,906	11,249	22,001	21,393	21,950	4.09	4.63	4.78
V. stress	62	6375	5913	6721	12,002	13,003	14,441	2.76	3.27	4.22
V. stress	275	9344	9036	9029	17,146	18,465	19,141	3.70	3.89	4.73
Waipio, Hawaii study										
UH610	0	2136	3675	2577	6912	10,036	7736	3.18	3.82	3.42
UH610	50	4458	5175	4460	11,095	13,758	12,286	3.74	4.51	4.36
UH610	200	6758	6609	6482	15,655	17,815	17,853	4.60	4.94	5.00
Pio 304	0	2527	3369	2137	7801	9446	6878	3.24	3.71	3.17
Pio 304	50	5124	4850	4276	12,664	13,975	12,630	4.36	4.67	4.52
Pio 304	200	6489	6766	6603	15,722	19,132	19,243	4.58	5.16	5.21

Rainfed, no irrigation; V. Stress, vegetative stress irrigation treatment; Irrigation, full irrigated irrigation treatment; Pio 304, maize variety Pioneer 304; UH610, maize variety UH610.

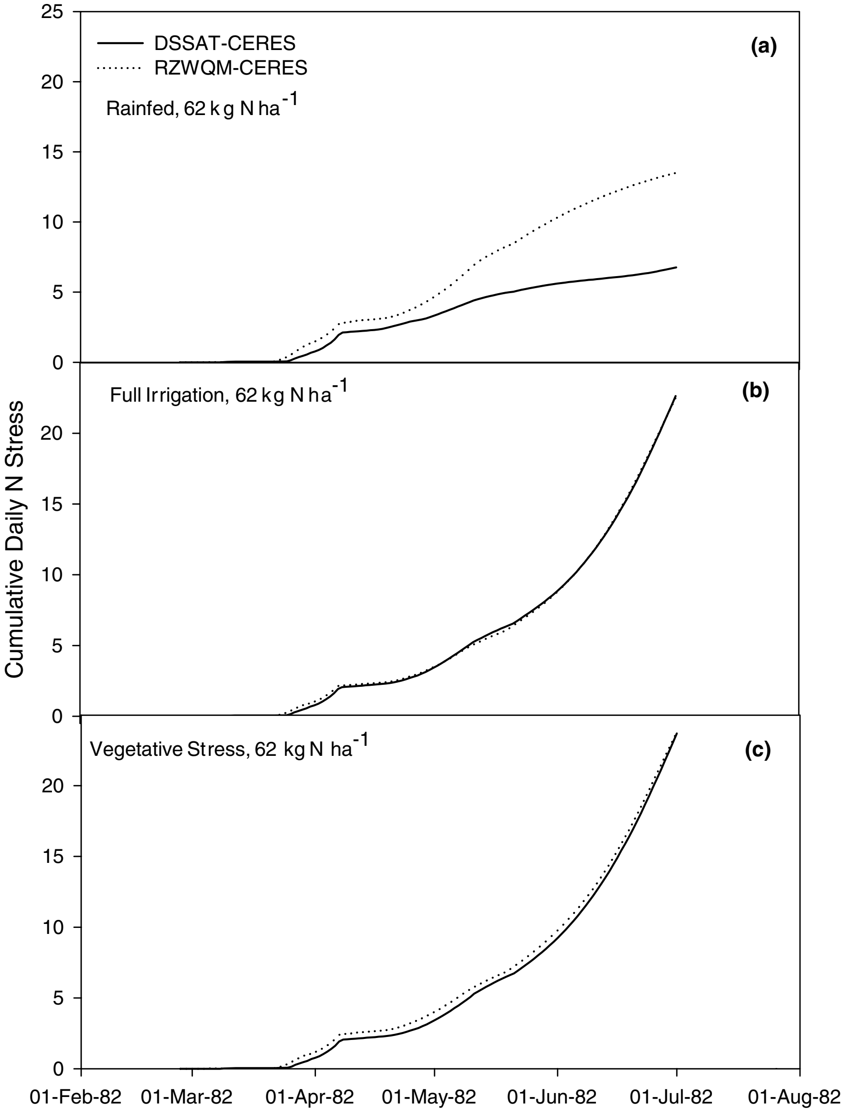

Fig. 5. Simulated cumulative daily nitrogen stress factors by the RZWQM-CERES and DSSAT-CERES models for the 62 kg N ha^{-1} treatment for rainfed (a), vegetative stress (b), and full irrigated (c) treatments of the Gainesville, Florida study.

4.3. Maize production simulation

Success of a crop growth model relies on a correct simulation of the soil water and N stress factors. For the Gainesville, Florida study, both models simulated the highest water stress under rainfed conditions and no water stress under full irrigation,

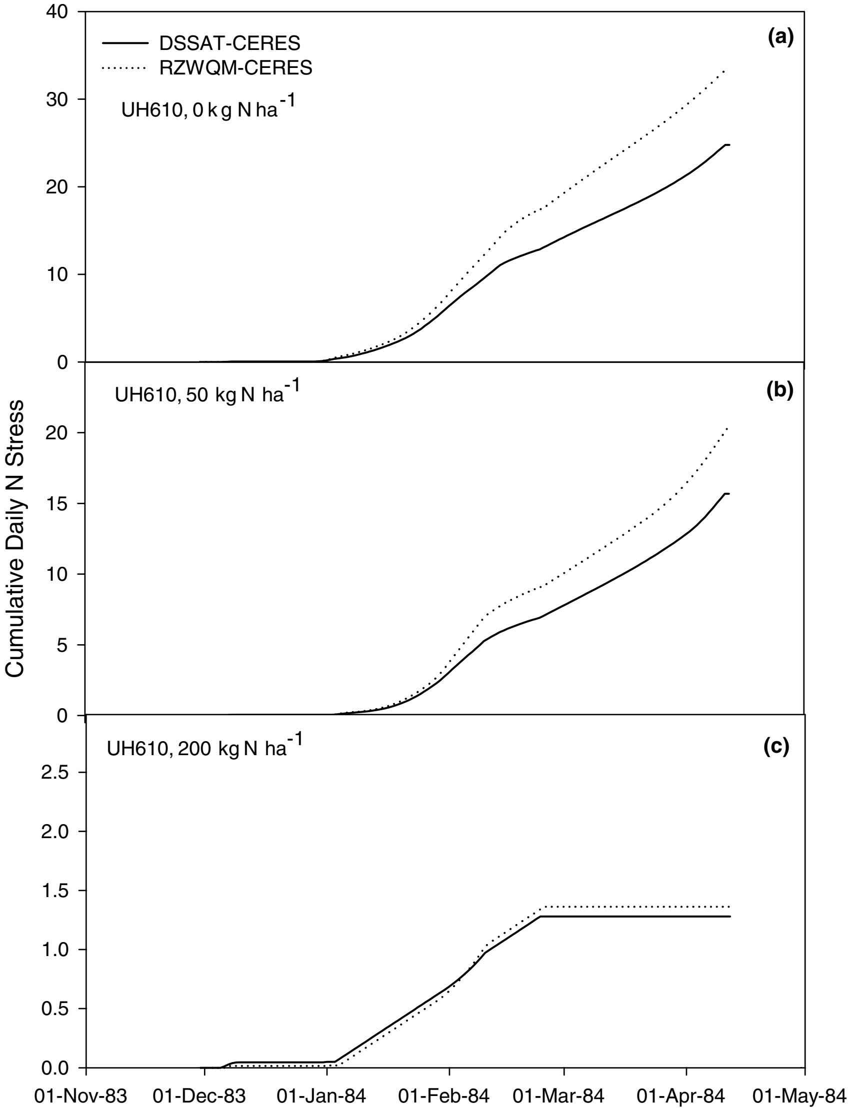

Fig. 6. Simulated cumulative daily nitrogen stress factors by the RZWQM-CERES and DSSAT-CERES models for the UH610 variety at 0 kg N ha^{-1} (a), 50 kg N ha^{-1} (b), and 200 kg N ha^{-1} (c) N application rates of the Waipio, Hawaii study.

regardless of N treatments (Fig. 3). The cumulative daily water stress factors, averaged across all the treatments, were 23.8 for the rainfed treatment, 6.3 for the vegetative stress treatment, and 0.1 for the full irrigation treatment in the DSSAT-CERES model. The corresponding cumulative daily water stress factors were 17.2, 2.7, and 0 for the RZWQM-CERES model. For the Waipio, Hawaii study, no water stress was simulated for the 0 and 50 kg N ha^{-1} treatments and very minor water stress for the 200 kg N ha^{-1} treatment (1.7 in terms of cumulative daily water stress factors) in the DSSAT-CERES model, whereas the RZWQM-CERES model simulated very minor but similar water stress for all the N treatments (about 2.0 in terms of cumulative daily water stress) (Fig. 4).

The cumulative daily N stress factors during the crop growing seasons also responded well to the irrigation and nitrogen treatments. For the Gainesville, Florida study, N stress increased with an increase in irrigation amount because of N leaching, and decreased with an increase in N fertilization rate (Fig. 5). The RZWQM-CERES model simulated a similar N stress for all treatments as the DSSAT-CERES model, except under rainfed condition with a 62 kg N ha^{-1} application rate (Fig. 5). Under irrigated conditions, the average cumulative daily N stress was 23.5 for the 62 kg N ha^{-1} treatment and 3.8 for the 275 kg N ha^{-1} treatment in both models. Under rainfed conditions, the cumulative daily N stress factors were 13.6 for the RZWQM-CERES model and 6.8 for the DSSAT-CERES model for the 62 kg N ha^{-1} application rate, and 1.2 for the 275 kg N ha^{-1} application rate for both models. Similar conclusions were drawn from the Waipio, Hawaii study, where N stress decreased with increase in N fertilization and the RZWQM-CERES simulated higher N stress at lower N application rates (0 and 50 kg N ha^{-1}) and similar N stress at higher application rate (200 kg N ha^{-1}) than the DSSAT-CERES model (Fig. 6).

Maize production was evaluated based on model prediction of biomass and yield at final harvest and during the growing seasons. Harvested biomass and yield and maximum LAI are listed in Table 4. Both models correctly simulated the trends of yield and biomass responses to irrigation and N treatments. Simulated maximum LAI was comparable from both models for the Waipio, Hawaii study, whereas the RZWQM-CERES model simulated higher maximum LAI than the DSSAT-CERES model for the Gainesville, Florida study due to less water stress simulated in the RZWQM-CERES model (Table 4). The RMSE for simulated yield across all the treatments for the Gainesville, Florida study was 695 kg ha^{-1} for DSSAT-CERES model and 537 kg ha^{-1} for the RZWQM-CERES model with no significant difference in yield simulation based on the paired *t* test. The corresponding RMSE for the Waipio, Hawaii study was 792 and 438 kg ha^{-1} without significant difference between the two models either. The RMSE for simulated biomass across all the treatments for the Gainesville, Florida study was 913 kg ha^{-1} for the DSSAT-CERES model and 1894 kg ha^{-1} for the RZWQM-CERES model. Simulated higher biomass in RZWQM-CERES than in DSSAT-CERES was closely related to simulated higher maximum LAI (Table 4). The corresponding RMSE for the Waipio, Hawaii study was 2502 and 1834 kg ha^{-1}. Again no significant difference was found in biomass predictions between the two models.

The models were further tested for their simulations of LAI, gain weight, and biomass during the crop growing seasons. The RMSE for simulated grain weight across all the treatments was 551 and 479 kg ha^{-1} for the RZWQM-CERES model and the DSSAT-CERES models, respectively, for the Gainesville, Florida study. The corresponding RMSE for the Waipio, Hawaii study was 978 and 1023 kg ha^{-1} for the

RZWQM-CERES and the DSSAT-CERES models, respectively. No significant differences were found for both datasets in grain weight predictions during the growing seasons in both studies. Simulated biomass was comparable for the Waipio, Hawaii study with RMSEs of 1585 kg ha^{-1} (RZWQM-CERES) and 2587 kg ha^{-1} (DSSAT-CERES). The RMSE for simulated biomass across all the treatments for the Gainesville, Florida study was 1760 kg ha^{-1} in RZWQM-CERES model and 1111 kg ha^{-1} for the DSSAT-CERES model. This difference in biomass prediction was significant based on the paired *t* test ($p < 0.001$), although no difference was found for final biomass at harvest (Table 4). RZWQM-CERES model had a better LAI simulation for the Waipio, Hawaii study with an RMSE of 1.81 (RZWQM-CERES), compared to a RMSE of 1.92 for the DSSAT-CERES model with $p < 0.001$. In contract, the DSSAT-CERES model simulated LAI better for the Gainesville, Florida study with an RMSE of 1.00 (DSSAT-CERES) compared to an RMSE of 1.37 for the RZWQM-CERES model with $p < 0.001$.

Therefore, there were no consistent differences between the RZWQM-CERES hybrid model and the original DSSAT-CERES-Maize model in the simulation of maize production, based on the two datasets. The hybrid model seemed to be better for the Waipio, Hawaii study and the DSSAT-CERES model was better for the Gainesville, Florida study. As shown early, RZWQM-CERES model simulated less drainage and runoff than DSSAT-CERES-Maize model in the Gainesville, Florida study, which contributed to less water stress, higher LAI, and higher biomass simulated by the RZWQM-CERES model, especially under rainfed conditions. Thus, some calibrations to soil hydraulic properties would improve simulation results further by RZWQM-CERES model. Also, as shown by Ma et al. (2005) and Sau et al. (2004), a slight modification to the soil and plant parameters should improve the results due to a different PET and soil N used in the hybrid model. However, these additional calibrations to the hybrid model are beyond the scope of this study and will not add substantially to the content of this paper.

5. Summary and conclusion

In this study, we developed a hybrid model between the RZWQM and the CERES-Maize models and evaluated the hybrid model with two well-documented experimental datasets distributed with DSSAT v3.5. In the hybrid model, the RZWQM module provided the CERES-Maize module with daily soil N, water content, and potential evapotranspiration, while the CERES-Maize module supplied the RZWQM module with daily water and N uptake, and plant growth variables (e.g., LAI and root distribution). After final harvest, the non-harvestable plant parts were returned to RZWQM to update the soil residue pools. Both models were run using the same soil and plant parameters with only the soil carbon pools calibrated in the hybrid model to match the N mineralization rates of the CERES-Maize model.

The RZWQM-CERES-Maize model provided comparable simulation results for yield, biomass, LAI, and N uptake as the original DSSAT-CERES-Maize model, and responded similarly to irrigation and N treatments. These results suggest successful coupling of the two models, and are in agreement with Ma et al. (2005) who found that the RZWQM-CROPGRO hybrid model provided similar crop growth simulation when the estimated PET was similar. However, some adjustments to soil and plant parameters were inevitable when the estimated PET from Shuttleworth and Wallace (1985) was higher than that from Priestley and Taylor (1972) (Ma et al., 2005; Sau et al., 2004). This hybrid model is a new model and offers RZWQM users an access to a more rigorous plant growth model and DSSAT users a tool to simulate macropore flow, tile flow, water table fluctuation, pesticide fate, soil microbial population, and other management effects (e.g., tillage, manure application, and crop residue effect). In this study, The RZWQM-CERES model was evaluated only for maize production using default or DSSAT-CERES derived parameters to demonstrate a valid and successful coupling of two models. A complete dataset with measured soil water and nitrogen balance is needed to evaluate the soil components of the hybrid model. Further studies will evaluate and improve the hybrid model for both crop production and environmental quality under a wide range of management scenarios.

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